10

Early High-Energy Upper Stages

During the 1950s, interest in high-energy propellants for upper stages of rocket vehicles had steadily mounted. Such propellants were initially seen as a means for increasing the range of ballistic missiles, but this shifted early towards increasing the capability of rockets to launch satellites and space probes. The principal candidates were hydrazine-fluorine, hydrogen-oxygen, and hydrogen-fluorine, but none had reached the development stage. The coming of Sputnik and U.S. plans for a strong space program quickly produced action; the first high-energy upper stage authorized for development used liquid hydrogen–oxygen. The decision, and subsequent development, owed much to an earlier program, which had faltered—Suntan, the program to develop a high-altitude reconnaissance airplane fueled with liquid hydrogen (chap. 8).

Legacy of Suntan

The Pratt & Whitney Aircraft division of United Aircraft Corporation was operating the first 304 hydrogen-fueled engine in the initial series of Suntan tests at the Florida test center when Sputnik was launched. At that time there was no indication that Suntan was soon to end, but neither this possibility nor Sputnik caught the astute Perry Pratt napping. About two years earlier, he had recruited C. Branson Smith from the Hamilton Standard division of United Aircraft, and one of his first assignments was to study the possibilities for Pratt & Whitney's entry into the rocket field.[1] With the Rocketdyne division of North American Aviation and Aerojet-General Corporation the giants in the large liquid-propellant rocket engine business, and Bell Aircraft and the Reaction Motors division of Thiokol smaller but very aggressive, it was obvious that a newcomer would need to do something new and different. As the division began to move fast on the hydrogen-fueled engine for Suntan in early 1956, Smith found his answer. In April 1956, he jotted down in his work log two subjects of potential interest: hydrogen as a high-energy fuel and pentaborane as a storable fuel. Smith's approach to rocket work was methodical: educate the staff, make an evaluation of rockets to establish the best type on which to concentrate, and propose an experimental contract to gain experience and advance the basic technology. In May 1956, Smith briefed Pratt on early results. From this meeting came a decision to summarize the status of hydrogen rocket engine work, to consider rocket engines for aircraft auxiliary

propulsion, and to consult with Wesley Kuhrt on the air turborocket. Smith visited the Los Alamos Scientific Laboratory and learned about their nuclear rocket. Although ammonia was to be the working fluid in early tests, Los Alamos was also interested in using hydrogen; the Livermore Laboratory, also working on nuclear rockets, had definitely planned to use hydrogen. Smith learned a great deal about hydrogen at Los Alamos and at the Bureau of Standards cryogenic laboratory in Boulder. He submitted his report on rockets to Pratt in June and revised it the next month. He concluded that: (1) in the next decade the rocket would become capable of performing most military missions at greater speeds and altitudes than gas turbine powered aircraft, (2) the most immediate application for Pratt & Whitney was an auxiliary thrust rocket to increase aircraft performance, and (3) in the missile field the ultimate fuel was hydrogen. Smith saw the first step for the division as a general educational program; the second step, the development of a small rocket for boosting aircraft in combination with gas turbine engines; and the third step, to propose hydrogen for long-range ballistic missiles. Smith added that the division's present and anticipated experience with hydrogen offered an opportunity to overtake existing rocket competitors.[2] Although this is what happened later, Smith's recommendations did not produce immediate action. Pratt & Whitney was fully engrossed in the Suntan program to use hydrogen in a modified J-57 and in developing the 304 engine. By the fall of 1956, Smith was making calculations of hydrogen and oxygen as coolants, and in November he visited NACA's Lewis laboratory to learn about work on hydrogen as a rocket fuel with oxygen and fluorine as oxidizers.

On 4 April 1957, Smith and Pratt made a presentation on hydrogen-fueled rockets at a management meeting of United Aircraft officials.* As a result, Pratt asked Smith to prepare a proposal for the first phase of a hydrogen rocket program. He was to make a cost estimate, note the limited availability of hydrogen, and consider a possible substitute fuel. Apparently, the United Aircraft management was willing to get involved in rocket work, but not wholly convinced that liquid hydrogen was the best fuel. In mid-April Smith was among a group of engineers who met with the Navy on boron fuels. After the meeting, Pratt took Smith to visit Col. Norman C. Appold, the Suntan manager, at the Air Force's Air Research and Development Command headquarters in Baltimore. They proposed that Pratt & Whitney develop a liquid hydrogen–liquid oxygen rocket engine, but Appold was not receptive; he wanted Pratt & Whitney to concentrate on Suntan objectives.

In July 1957, Smith summarized a year's thinking about rockets. In propellant evaluation, he indicated that hydrogen led for vehicles requiring maximum performance, such as ICBMs, satellites, and space ships. Hydrogen was well-suited for long-range missiles and could halve the gross mass of those being developed using kerosene and oxygen. He also saw advantages for hydrogen for shorter-range missiles, particularly stages that must accelerate to very high velocities. The substitution of hydrogen for kerosene in the second stage of an ICBM would increase the payload 50 percent without increasing the gross mass. Alternately, ICBMs then being developed could place payloads into a satellite orbit by using hydrogen in the second stage. He recommended to Pratt that a vigorous effort be mounted to develop a hydrogen-

*H. M. Horner, L. S. Hobbs, W. P. Gwinn, W. A. Parkins, and B. McNamara.

oxygen rocket engine. Smith also considered boron fuels and solid propellants in his review and proposals to the Navy and Air Force.[3]

On 25 July 1957, Smith visited the power plant laboratory at Wright Field and made a presentation featuring hydrogen as a rocket fuel for a 267 kilonewton (60000 lb thrust) second stage for an ICBM. Because of the classification of Suntan, he omitted telling his audience about the considerable experience Pratt & Whitney had amassed with liquid hydrogen.* The reaction of the Wright Field group to Smith's presentation was that his results appeared reasonable, but hydrogen had not been pursued previously because of its high cost and low availability. Smith was encouraged enough by the reactions to complete a proposal in August, but nothing came of it. It was the same month that the first 304 hydrogen expander engine was assembled at the East Hartford plant for shipment to the Florida test center and two months before Sputnik I.

The Air Force had ample precedent, in previous work at Ohio State University in the 1940s, to be interested in hydrogen for rockets. The fuels and propulsion panel of the Air Force Scientific Advisory Board foresaw the need for a hydrogen-fueled rocket a year before Sputnik I. At the panel's meeting on 14 November 1956, high-energy propellants were considered for upper stages of high-performance rockets. The panel, of which Abe Silverstein was a member, recommended that two rocket engines be developed in the 111 to 222 kilonewton (25000–50000 lb thrust) size using high-energy chemical propellants.† Liquid hydrogen–oxygen was singled out as being a particularly attractive high-energy combination. The panel was aware of the Air Force's plants which had been built to produce liquid hydrogen in quantity for the "air-breathing super fuel program" (i.e., Suntan) and that ample quantities would be available for testing. The ballistic missile program used vast amounts of liquid oxygen, so the panel thought the time for using the hydrogen-oxygen combination had come.[4]

Although the minutes do not single out the contributions of individual members, the influence of Abe Silverstein is unmistakable. He had been intensely interested in liquid hydrogen as an aircraft fuel since 1955 and was directing a strong research program on it. As early as 1950, he had organized a meeting of government and industry rocket experts on the subject of high-energy rocket propellants for long-range missiles (p. 76). At the 1950 meeting, the rocket group at the NACA Lewis laboratory had recommended liquid hydrogen as their first choice for fuel, with hydrazine and ammonia as alternatives. Fluorine was the favored oxidizer, with oxygen as the alternate. At the time of the panel meeting, hydrazine or ammonia with fluorine, and hydrogen with fluorine or oxygen, were the high-energy combinations of greatest interest in the country. Prior to its meeting, the panel had visited the NACA Lewis laboratory, the Air Force power plant laboratory, and Pratt & Whitney.

The Air Force waited over a year (until December 1957) to reply to the board's recommendations. With respect to rocket engines using ammonia-fluorine, the Air Force cited a contract with Bell Aircraft on experiments with a 156 kilonewton (35000 lb thrust) chamber using ammonia-fluorine. With regard to hydrogen-oxygen, the Air

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*Col. Appold, the Air Force's Suntan manager, had visited the laboratory the previous day and presumably had informed the staff about Pratt & Whitney's hydrogen experience.

†Dr. Mark M. Mills was chairman; other members attending, besides Silverstein, were Dr. W. Duncan Rannie of JPL and C.I.T. and Dr. Edward S. Taylor of M.I.T.

Force commented that six months previously (about June 1957), Wright Field had prepared a procurement request for a liquid-hydrogen engine, but did not send it to industry because of NACA work with this combination. The November 1957 NACA firing of a liquid hydrogen–fluorine rocket (p. 92) was cited. The Air Force intended to follow through when NACA completed its exploratory work—an indication that the Air Force felt no great rush for action, two months after Sputnik I.[5] This was consistent with the disappointments Pratt & Whitney was experiencing in trying to sell the Air Force a hydrogen-oxygen engine. The stimulus needed was to come later in a negative way—the demise of Suntan.

During the remainder of 1957 and the early part of 1958, Smith and his group at Pratt & Whitney continued to work on the analysis of hydrogen cycles and the layout of engines with thrusts ranging from 31 to 133 kilonewtons (7000 to 30000 lb). Exploratory meetings were held with the Air Force, and on 4 March 1958, Perry Pratt sent to the ARDC a preliminary design and proposal for a 68 kilonewton (15000 lb thrust) advanced rocket engine using liquid hydrogen and liquid oxygen as propellants.[6] It was intended for the Air Force's growing astronautics program and specifically for applications being developed by the Missile Systems Division of Lockheed Aircraft Corporation. Lockheed was studying advanced versions of its WS117L reconnaissance satellite, and their work indicated a thrust level of about 31 kilonewtons (7000 lb). Lockheed, however, wanted to use fluorine instead of oxygen with hydrogen.

The hydrogen-fluorine combination produces peak performance using a smaller proportion of hydrogen than the hydrogen-oxygen combination; when this is coupled with the greater density of fluorine over oxygen, the result is a much more compact stage for the same thrust and duration. (Lockheed was also very interested in an even denser combination, hydrazine-fluorine.)

By the spring of 1958, the Suntan management team at ARDC decided that the time had come for a rocket engine using liquid hydrogen to power an upper stage.[7] They were aware of the Lockheed studies and the efforts of Krafft Ehricke of Convair-Astronautics to sell ARDC a Mars probe using a hydrogen-oxygen stage on top of the Atlas intercontinental missile.

The Suntan team may have hedged on the selection of oxidizer. Liquid oxygen was the safest choice, but fluorine was also of interest.* The team coordinated the proposal with Brig. Gen. Marvin C. Demler, deputy commander of ARDC, and it was signed by Lt. Gen. Sam Anderson, the commander. The proposal was addressed to Gen. Thomas C. White, Air Force chief of staff, but the air staff decided to pass it to Richard E. Horner, the assistant secretary of the Air Force for research and development.[8] Horner had followed the Suntan work closely and was aware of its coming termination and the desirability of finding an application for the new technology. The Suntan management team arranged a briefing for him and brought in Pratt & Whitney representatives to strengthen their presentation. Horner favored the proposal, but decided it should be

*In addition to Lockheed's interest in fluorine, three of the Suntan team—Col. Norman C. Appold, Lt. Col. John D. Seaberg, and Capt. J. R. Brill—had attended the NACA conference in November 1957 that was devoted largely to liquid hydrogen as a fuel, including data from the firing of a liquid hydrogen–fluorine rocket.

sent to Roy Johnson, director of the Advanced Research Projects Agency which was heading military space coordination. Johnson and his staff were briefed on 13 June 1958 (the day following a briefing of the Air Council on Suntan). Horner also arranged for ARPA staff members to visit the Suntan liquid hydrogen facilities in July 1958. Richard Canright and David Young, both well acquainted with hydrogen, were greatly impressed at seeing liquid hydrogen being pumped through nearly a half kilometer of piping at Pratt & Whitney's Florida test center. The Air Force made a persuasive case for ARPA to choose Pratt & Whitney for the development of a liquid hydrogen rocket, based on the division's experience in building a hydrogen expander engine for Suntan and the ready availability of a large supply of liquid hydrogen.[9]

While the Suntan team was making a bid within the government to develop a hydrogen-fueled rocket, Smith and others at Pratt & Whitney revised their March 1958 proposal to the Air Force to conform with Lockheed Aircraft desires and resubmitted it on 5 May 1958. In the following weeks, the two companies cooperated in analyses and layouts of five different propulsion systems, all for a proposed advanced reconnaissance satellite. During this period there were many reviews of the work by Air Force and ARPA representatives. At one such meeting on 9 July 1958, Air Force, ARPA, Lockheed, and Pratt & Whitney representatives unanimously agreed to select liquid hydrogen and liquid oxygen as the propellants and a thrust level of 53.5 kilonewtons (12000 lb). Nine days later, Pratt & Whitney engineers drafted engine specifications and a proposal for company approval before sending them to ARDC. The engine was to be developed in 18 months at a fixed price of $19.8 million.[10] Essentially the same engine was in fact developed later as the RL-10.

In August 1958, the ARDC was authorized to proceed with the development of a hydrogen-oxygen engine. Its application was not for a Lockheed-built stage, however, but for a stage proposed by General Dynamics–Astronautics.

Origins of Centaur

The first rocket stage to fly using liquid hydrogen and liquid oxygen as propellants was the Centaur stage on top of an Atlas intercontinental ballistic missile. Centaur was the brainchild of Krafft Ehricke. For nearly three decades, Ehricke had prepared himself for the space age; when it dawned with Sputnik, he was ready. Within a month, he proposed a hydrogen-oxygen stage for use with the Atlas missile. Ehricke was able to move rapidly because previous work on the Atlas missile and the ideas of others about hydrogen-oxygen upper stages had laid the groundwork.

Ehricke became a space enthusiast at the age of eleven when he was captivated by Fritz Lang's "Girl in the Moon," shown in Berlin in 1928. Advanced in mathematics and physics for his age, he appreciated the great technical detail that Hermann Oberth had provided to make the film realistic. Young Krafft became acquainted with Tsiolkovskiy's space rocket using hydrogen-oxygen, which he read about in Scherschevsky's *Die Rakete fuer Fahrt und Flug*. He also tackled Oberth's *Wege zur Raumschiffahrt* in his early teens, but was slowed by the mathematics. Ehricke graduated from the Technical University in Berlin (aeronautical engineering) and took postgraduate courses at the Humboldt University in celestial mechanics and nuclear physics. He was conscripted into the army, served in a Panzer division on the

Russian front during World War II, but was recalled and reassigned to rocket development work at Peenemünde in June 1942. There he came under the strong influence of Walter Thiel, in charge of rocket engine development, who was killed in the first British air raid on Peenemünde in October 1943. Peenemünde, under Maj. Gen. Walter Dornberger and Wernher von Braun, his technical director, had a single purpose—the rapid development of specific weapons—and there was no official tolerance of work not directly related to the main goal. In spite of this, Thiel shared Ehricke's desire to look beyond the immediate future to greater possibilities. Thiel himself drew plans for testing rockets larger than any yet dreamed of—on the order of 5–14 meganewtons (1–3 million lb thrust). He wanted to use natural gorges in Bavaria as testing sites. He talked to Ehricke about resuming his own earlier experiments with liquid hydrogen in small rocket thrust chambers. The experiments of Heisenberg and Pohl with a nuclear reactor using heavy water excited Thiel. When he heard that Heisenberg was planning to operate a turbine with steam heated by the heavy water reactor, Thiel urged Ehricke to study the possibilities of using nuclear energy for propulsion. Ehricke considered several working fluids, but both he and Thiel favored hydrogen and believed it was a fuel with a future.[11]

As the war was ending, Ehricke helped move Peenemünde records into Bavaria, to keep them out of Russian hands. He made his way on foot to Berlin where he found his wife and went into hiding until the Western Allies moved in. He was located by the U.S. Army, given a six-month contract, and came to the United States to rejoin the von Braun team as part of the Paperclip operation.*

Ehricke and von Braun recalled another time they had considered hydrogen. In 1947, von Braun asked Ehricke to check a report by Richard B. Canright of the Jet Propulsion Laboratory on the relative importance of exhaust velocity and propellant density for rockets of the V-2 size and larger (pp. 47–48). It had caught von Braun's attention because he and two associates had written a paper the previous year which Canright had cited.[12] Von Braun had found, under the assumptions of fixed tank volume and a relatively heavy structural mass, that propellants with the highest densities and reasonably high exhaust velocities had the greater ranges. Canright, on the other hand, found that for large rockets and his assumptions (which included a variable tank volume and relatively light structural mass), exhaust velocity was decidedly more important than density. Canright's analysis showed hydrogen to be superior to other fuels when using the same oxidizer. Both Ehricke and von Braun, familiar with Oberth's case for using hydrogen-oxygen in upper stages of rockets (appendix A-2), agreed that hydrogen had a good potential for certain applications. Practical experience with liquid hydrogen in rockets at that time, however, was still very small and its handling problems large. The Army, for whom von Braun and Ehricke worked, wanted practical propellants that could be stored and handled safely in the field. This convinced von Braun to stick to well tested and denser propellants, but Ehricke felt less restrained and hydrogen's potential remained prominent in his thinking.

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*Ehricke wanted to work for the Americans, and he hid each time someone knocked on his door, waiting for the right caller. One day his wife answered the door and routinely said, "I don't know where he is." As she did so, she recognized the insignia of a U.S. Army officer and immediately began screaming, "He's here! He's here!" Interview, 26 Apr. 1974. Paperclip was the project for bringing German rocket experts to the United States.

Fig. 49. Krafft A. Ehricke, father of the first hydrogen-oxygen stage, Centaur, shown receiving the Loesser award at the 1956 International Astronautical Congress, Rome. (Courtesy of F. C. Durant, III.)

In 1950, Ehricke moved with von Braun to Huntsville, Alabama, but grew restless with both the climate and von Braun's conservative engineering. He joined Walter Dornberger at Bell Aircraft in 1952. Bell, then busy developing the Agena upper stage, also proved to be unable to offer Ehricke the opportunity for a breakthrough he was looking for; and in 1954, when K. J. Bossart of Convair contacted him to work on the Atlas ICBM, he was ready to move. Soon after, the Air Force established the Ballistic Missile Division under Brig. Gen. Bernard Schriever to accelerate development of the Atlas. Schriever insisted on total dedication to the job at hand and Ehricke found himself again in the same atmosphere as at Huntsville and Peenemünde. In Charlie Bossard, however, Ehricke found a man of kindred spirit who, like Walter Thiel at Peenemünde, encouraged him to think beyond the immediate task. To imaginative Ehricke, this attitude and the climate and atmosphere of southern California were heaven.

By 1956, Ehricke was conducting in-house studies of vehicles for orbiting satellites. He approached the Rocketdyne Division of North American Aviation to obtain preliminary design data on various rocket propulsion systems employing turbine-driven pumps. He did not have much luck in getting government interest for his proposals, although he was a passionate believer in space exploration and a very persuasive person. The first week in October 1957, he visited Maj. George Colchagoff at ARDC headquarters. Ehricke had gotten wind of the Suntan project and was hoping to gain support for launching a satellite. It was the austere period under Secretary of Defense Charles Wilson, when "space" was out of favor. Although Colchagoff was receptive and personally convinced of the value of spaceflight, the official position made it difficult for Ehricke to round up support. On the Monday following Sputnik I's flight, however, Ehricke found many who indicated they had always favored spaceflight and now felt free to talk to him.

Excited by the new atmosphere, Ehricke returned to San Diego and began to streamline his plans. A. G. Negro, a Rocketdyne applications engineer, visited Convair on 11 October 1957 and returned with a request for information on a small pressure-fed rocket engine using liquid hydrogen and liquid oxygen. It was to produce 31 kilonewtons (7000 lb of thrust) and be capable of restart at altitude. By the end of October, Negro established the design characteristics of the engine, including a combustion pressure of 4 atmospheres and exhaust velocity of 4030 meters per second.[13]

In December 1957, General Dynamics–Astronautics submitted a proposal to the Air Force entitled, "A Satellite and Space Development Plan." It was for a four-engine, pressure-fed hydrogen-oxygen stage with each engine developing 31–33 kilonewtons (7000–7500 lb of thrust). According to Ehricke, "The reason why we selected this engine system in teamwork with the Rocketdyne Division of N.A.A. was simply that we wanted to avoid the delay by what we thought would have to be a brand new pump development. We were, for security reasons, not aware of the Pratt & Whitney's pioneer work in this field."[14]

The Air Force did not buy the specific General Dynamics–Astronautics proposal, but in the following months activities within the government clearly foreshadowed an emerging space program. Among these, General Dynamics–Astronautics and Pratt & Whitney were brought together by the Air Force and the Advanced Research Projects

Agency and in August 1958 were authorized to proceed with the development of the Centaur stage, the first to use liquid hydrogen and liquid oxygen.

NASA Plans, ARPA Acts

The ink was hardly dry on the President's signature establishing NASA on 29 July 1958 when Abe Silverstein established a committee to coordinate government plans for propulsion and launch vehicles. He called it an informal technical advisory committee for propulsion with himself as chairman. It had a flexible membership to meet the needs that arose.*

At the first meeting on 7 August 1958, the agenda included high-energy upper stages. Recognizing that a choice of the best high-energy propellant combination depended upon the application and stage design, a working group was appointed to review available information and present it to the committee for evaluation. Headed by A. O. Tischler, a propulsion researcher Silverstein recruited from the NACA Lewis laboratory, the working group was instructed to give particular attention to hydrogen-oxygen and hydrogen-fluorine.† In so doing, the Silverstein committee also agreed to defer a contract then under consideration by the Air Force to develop a hydrazine-fluorine engine of 356 kilonewtons (80000 lb thrust).[15]

At the second meeting of the Silverstein committee on 14 August, discussion of the high-energy propellant stages centered around a hydrazine-fluorine engine of 53 kilonewtons (12000 lb thrust), being developed by Bell Aircraft for the Air Force, and a contract just awarded by Wright Field to Aerojet-General to study the feasibility of a hydrogen-oxygen engine of 445 kilonewtons (100000 lb thrust). However, no actions were taken on these.[16]

By the time of the third meeting of the Silverstein committee on 28 August 1958, the Tischler working group on high-energy upper stages reported progress.‡ Hydrazine-fluorine engines in thrust ranges from 27 to 90 kilonewtons (6000 to 20000 lb) were marginally superior to hydrogen-oxygen engines for a well-designed stage using tank pressurization to force propellants to the engine. A hydrogen-oxygen engine using a turbopump, however, was superior to a hydrazine-fluorine engine of the same thrust using tank pressurization instead of pumping. Hydrogen-fluorine engines were lighter than engines using the two other propellant combinations.[17]

According to Silverstein and Tischler, this meeting provided the impetus for final actions by ARPA on a hydrogen-oxygen engine. Cesaro reportedly slipped out of the meeting and telephoned his associates to move fast on the Centaur proposal.[18]

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*Attendees at the initial meeting were: for ARPA, Dr. Arthur Stosick and Richard Cesaro; for the Air Force, Col. Donald Heaton, ARDC, and C. W. Schnare and William Rogers, WADC; for NASA, William Woodward and A. O. Tischler.

†Other members: R. B. Canright and R. S. Cesaro of ARPA; Joseph Rogers and Alfred Nelson, WADC; Alfred Gardner, ARDC; and M. L. Moseson, NACA-Lewis. Nelson was a propulsion analyst at Wright Field; Schnare was the chief rocket engine expert at Wright Field and Joseph Rogers worked for him. Moseson was a design specialist at NACA-Lewis.

‡Attendees: Dr. Jack Irvine, Richard Cesaro for ARPA; Col. Donald Heaton, C. W. Schnare, Joseph Rogers, Richard Shaw, and B. Chasman for ARDC; Lt. Col. Nils Nengtson for AOMC; Dr. Abe Silverstein, William Woodward, and A. O. Tischler for NASA.

Whether for this reason or by coincidence, ARPA issued order 19-59 the following day (29 August), directing the commander of ARDC to initiate a high-energy fuel stage for use with a modified Atlas missile. The propellants were to be liquid hydrogen and oxygen. The propulsion system was to be either pressure-fed or pump-fed, with a total thrust of 133 kilonewtons (30000 lb) in single or multiple units. The final design would be determined after detailed studies were made by the propulsion and vehicle contractors and review by ARPA. Preliminary flight rating testing was to be 18 months from go-ahead. The sole source for the engine contract was Pratt & Whitney Aircraft Division of United Aircraft Corporation, and the sole source of the vehicle was Convair-Astronautics Division of General Dynamics Corporation. ARPA would review and approve the design, development, and financial plan; provide policy and technical guidance; arrange technical direction; prescribe management and technical reports; and receive credit for technical and scientific information released on the project.[19]

In essence, ARPA bought Krafft Ehricke's modified Centaur proposal, and the wording of its order suggests that a fast decision was made before final proposals and designs were determined. The commander, ARDC, designated the special projects office, then headed by Lt. Col. John D. Seaberg, as responsible for implementing the order. This was the office formerly headed by Col. Norman Appold, who managed the Suntan project. Seaberg and others in the office, including Majors Alfred J. Gardner, Jay R. Brill, and Alfred J. Diehl, had all been a part of Suntan. Two days after the ARPA order, Pratt & Whitney conducted the tenth and final series of tests with the hydrogen-fueled 304 turbojet engine. Suntan became a thing of the past and Centaur, a hydrogen-oxygen rocket stage on top of Atlas, rose as its replacement. All the plant, equipment, and technology of Suntan could now be brought to bear in assuring that Centaur would succeed.

The impact of ARPA's order for Centaur was not immediately apparent to NASA, and Tischler's working group continued its study of high-energy upper stages, as a coordinated government effort. At the fourth meeting of the Silverstein committee on 11 September 1958, the working group on high-energy propellants had not heard from all pertinent contractors or assimilated all the data, but Tischler reported to the parent committee on the tentative results. He compared three propellant combinations—hydrogen-oxygen, hydrazine-fluorine, and hydrogen-fluorine—and systems using pressurized tanks versus systems using turbopumps. With payload capability as the criteria, conclusions were: (1) for pressurized systems, hydrogen-oxygen and hydrazine-fluorine were about equivalent; hydrogen-fluorine was 10–15 percent better in payload capacity; (2) systems with turbopumps were 5–15 percent better than pressurized systems; (3) hydrogen and oxygen had both been pumped successfully but pumping of fluorine needed further research; this reduced the comparison to pumped hydrogen-oxygen versus pressurized hydrazine-fluorine where the former has a 10–20 percent greater payload capability; and (4) a 53–62 kilonewton (12000–14000 lb thrust) rocket engine appeared best for a Thor first stage and two such engines would be suitable for an upper stage of the Atlas.[20]

At the fifth meeting of Silverstein's committee (25 September 1958) the agenda concerned liquid hydrogen pumping and storable propellants. Richard Coar and Walter Doll of Pratt & Whitney Aircraft discussed their experience with liquid

hydrogen pumps. One pump developed for "another purpose" (i.e., Suntan) had a flow rate of 2.2 kilograms per second with 17 hours of operation; a second pump had a flow rate of 45 kilograms per second with a delivery pressure of 54 atmospheres. They offered to deliver the latter pump in 18 months at a cost of $4.5 million. Stanley Gunn and Merle Huppert discussed Rocketdyne work on liquid-hydrogen pumps. They envisioned a six-stage, axial-flow pump. Tests of single stages of such a pump were scheduled for November, as part of the firm's work on the nuclear rocket. These presentations gave further evidence to the working group that pumping liquid hydrogen was not a major obstacle to the development of a pump-fed, hydrogen-oxygen rocket engine.[21]

Other than information exchange, the Silverstein committee took no action to initiate development of a high-energy upper stage. Tischler drafted plans for two sizes of hydrogen-oxygen engines but they were tabled. Alfred Nelson summarized high-energy propellants, engines, and stage designs. Thrust levels varied from 31 to 600 kilonewtons (7000 to 135000 lb). In NASA's first ten-year plan (November 1958), mention was made that hydrogen-oxygen upper stages in the 45 to 445 kilonewtons (10000 to 100000 lb thrust) range would be available.[22]

One of the eight organizations whose high-energy propellant data Tischler's working group had studied for the Silverstein committee* was the NASA Lewis laboratory, where both men still had close ties. Since the Lewis research continued to influence the former Lewis men in NASA headquarters, a summary of it during 1958–1959 is pertinent.

Lewis Hydrogen Rocket Experiments, 1958–1959

After their initial success in operating a hydrogen-cooled, hydrogen-fluorine rocket engine in November 1957 (p. 92), Howard Douglass, Glen Hennings, and Howard Price, Jr. continued the experiments until February 1959. Fourteen runs were made using the showerhead and triplet type of injectors with comparable results. A maximum exhaust velocity of 3455 meters per second was obtained at a flow rate that was 14 percent liquid hydrogen with a combustion pressure of 20 atmospheres. This was 97 percent of the maximum theoretical performance. The experimenters reported no problems relative to engine operation, starting, or stability of combustion. They did, however, have a number of minor problems with the injectors and with operating the thrust chamber beyond its design limits. Following this series of experiments, another team of researchers made 26 more runs with the same type of engine over a range of combustion pressures and exhaust nozzle expansion ratios. Earlier, Vearl Huff had suggested the technique of exhausting the rocket into a properly proportioned duct closed at the rocket end. The high-velocity rocket exhaust pumped the air from the duct, reducing the pressure in the immediate vicinity of the rocket nozzle and thereby simulated high altitude. The exhaust duct needed for silencing and for removing hydrogen fluoride from rockets using fluorine was ideal for the new purpose, so the one duct served three purposes. The nozzle altitude simulation

*Bell Aircraft, North American Aviation, Aerojet-General, General Dynamics–Astronautics, Martin, Space Technology Laboratories, Wright Air Development Center, and the NASA Lewis laboratory.

technique was used to test a rocket with a nozzle area ratio of 100 and the measured exhaust velocity was 4730 meters per second (at a combustion pressure of 49 atm), one of the highest performance values obtained by a chemical rocket engine.[23]

Cell 22, with its two parallel test stands capable of handling engines up to 22 kilonewtons, was the workhorse cell for high-energy propellants through 1957. A new, larger facility for high-energy propellants and engine thrusts up to 89 kilonewtons was ready for its first hydrogen tests on 14 November 1957. The initial run used gaseous hydrogen and a water-cooled chamber which leaked, causing ignition problems and a minor explosion, or a "hard start" in the rocket engineer's vocabulary. The chamber was repaired and five days later satisfactory starting was achieved, but other troubles arose. A malfunctioning indicator led the operator to increase propellant flows, and after a second of operation at a pressure of 30 atmospheres in a chamber designed for 20, the chamber burst. It was not a very auspicious start for the new facility, which continued to be plagued with propellant system, control, and instrument problems for several months. By mid-March 1958, fluorine was being used in the new facility and in the first week of May, liquid hydrogen. The climax to the series of facility problems also came in May when an experiment with gaseous hydrogen and liquid fluorine was conducted. Three successful runs were made and during a pause, with the propellant tanks still at high pressure, fluorine demonstrated its reactivity. A slight leak in a flanged joint at the top of the tank allowed fluorine to escape, and it immediately found substances with which to react. These reactions quickly heated the heavy stainless steel flange and pipe until they also reacted with the fluorine and with a swoosh, a column of fluorine shot upward, reacting with everything in its path, including water vapor in the air.[24] Fortunately, a wind quickly dispersed the fluorine compounds. The joint that leaked contained a soft aluminum seal that had been thermally cycled many times over a period of months with no leakage. It had been tested just prior to the ill-fated experiment and found satisfactory. These kinds of problems are normal in research where new ground is being plowed. The flange problem was solved by using welded joints, but the accident and the subsequent delay caused a shift in research plans. Work with hydrogen-fluorine at 22 kilonewtons in Cell 22 was proceeding well, and a decision was made to concentrate on hydrogen-oxygen at the new facility.

As regeneratively-cooled thrust chambers at 89 kilonewtons were not available, the first series of tests with gaseous hydrogen–liquid oxygen was made with uncooled chambers. The gaseous hydrogen was no handicap in this situation for it simulated the same physical state at the injector as liquid hydrogen after absorbing heat in a regeneratively-cooled jacket. Nineteen runs were made during 1958, with performance ranging between 94 and 99 percent of theoretical.[25]

Meanwhile, the 89 kilonewton, regeneratively-cooled engine became available and by June 1959, 32 runs were made with liquid hydrogen–oxygen. Run times varied up to 102 seconds and all showed satisfactory cooling and high performance. Later, an additional 14 runs, equally successful, completed the investigation and the results were reported in April 1960. Exhaust velocities up to nearly 3300 meters per second were obtained with a nozzle designed for sea-level operation, so even higher velocities were possible with a larger nozzle and operating at simulated altitudes. The investigators used a small quantity of gaseous fluorine flowing ahead of the liquid oxygen to spontaneously ignite with the hydrogen and provide a smooth start.[26] Figure 50 shows

a comparison of the 22 and 89 kilonewton, regeneratively-cooled engines used for the liquid hydrogen–fluorine and liquid hydrogen–oxygen experiments during the 1957–1959 period and later.

The injectors designed for both propellant combinations at both thrust levels followed the general concepts agreed upon at the August 1957 design conference (p. 89). They generally employed a large number of elements to promote vaporization and intimately mix the propellants. Some were impinging jets in triplet or doublet arrays, some were showerheads with either parallel or converging jets. All gave high, satisfactory performance. Figure 51 shows one of the injectors used with the 89 kilonewton engine.

The greatest value of research of this type is in advancing technology and getting someone else interested in using it for further advances. In the latter, the Lewis rocket research on hydrogen during the 1950s made two contributions. First, it influenced the views of Abe Silverstein, who began planning the NASA spaceflight program in the spring of 1958. He was greatly interested in hydrogen as a fuel, not only for rockets but for other applications. Silverstein followed the rocket work even after he went to Washington, and the May 1958 fluorine accident, which occurred while he was still commuting to the laboratory on weekends, reinforced his conviction that the performance gain by using the denser hydrogen-fluorine combination over hydrogen-oxygen was not worth the additional problems. The regeneratively-cooled hydrogen-oxygen operations at 89 kilonewton thrust in 1959 further convinced him that hydrogen-oxygen was by far the most attractive of the several propellant candidates

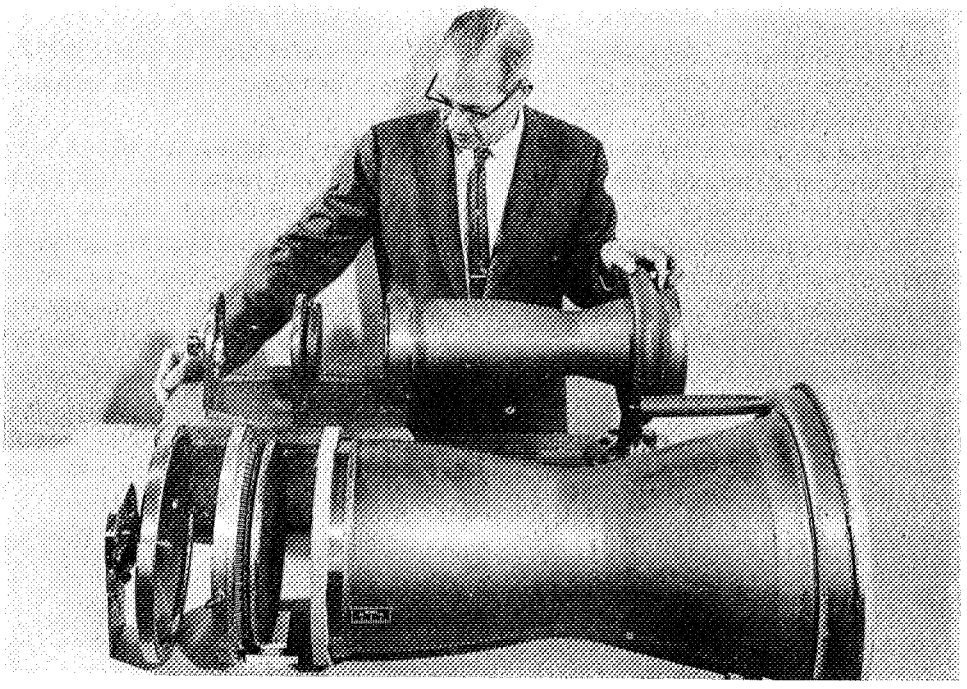

Fig. 50. The author with NACA's 22- and 89-kN regeneratively cooled rocket engines used for performance experiments of liquid hydrogen–fluorine and liquid hydrogen–oxygen, 1957–1959 and later.

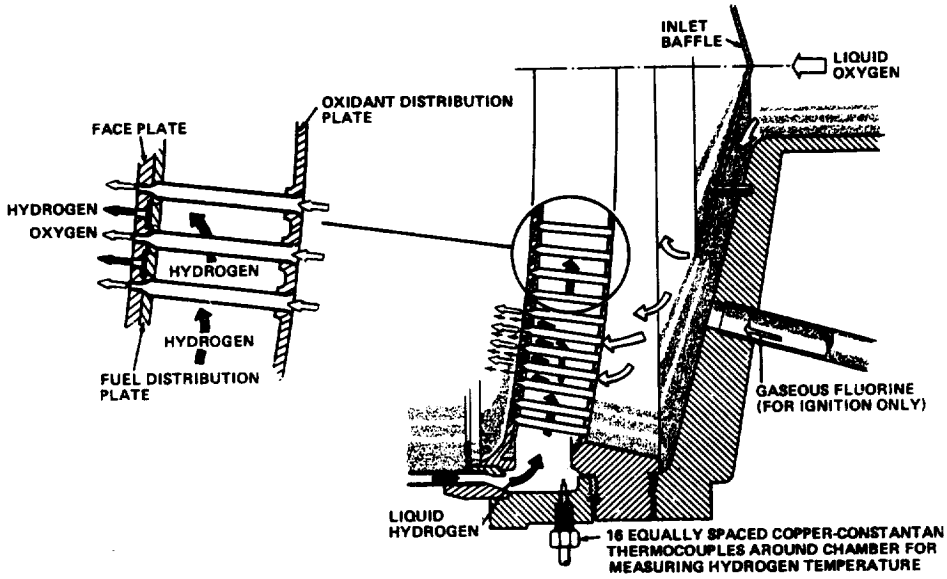

Fig. 51. Cross-section of an injector used in experiments with an 89-kN rocket engine using liquid oxygen and regeneratively cooled by the liquid hydrogen. A lightweight design, the injector was a converging showerhead type. Measured performance was 93 percent of theoretical. From Tomazic, Bartoo, and Rollbuhler, NASA TMX-253, Apr. 1960.

for high-performance rocket stages. His convictions were to have an important bearing on decisions made at the end of 1959, decisions that have determined the course of space vehicles to this day.

The second value of the Lewis hydrogen research was the influence it had on other rocket engineers. During 1959, 92 people from 42 organizations made 60 visits to the Lewis rocket laboratory. While not all were interested in hydrogen, the two major rocket engine manufacturers, Rocketdyne and Aerojet, each made three visits; Pratt & Whitney, with a go-ahead in August 1958 from the Air Force to develop a hydrogen-oxygen rocket engine for flight, made three visits during 1959. In fact, Pratt & Whitney representatives began visiting the Lewis rocket laboratory in 1957, much to the surprise of the laboratory officials who had previously found the company aloof when it came to exchanging information about aircraft engines.[27]

Transfer of Centaur

In October and November 1958, the Air Force let contracts with Pratt & Whitney and Convair to develop Centaur, the hydrogen-oxygen upper stage for Atlas. Also in October, NASA Administrator Keith Glennan requested ARPA Director Roy Johnson to transfer Centaur to NASA. This was agreed upon in principle by Deputy Secretary of Defense Donald Quarles by November. The Air Force, however, had missions requiring the Centaur vehicle and wanted to retain management control. As a consequence, both the Advanced Research Projects Agency and the Air Force

mounted strong efforts during the first part of 1959 to reverse the initial transfer agreement. NASA was well aware of the problem and on 6 May 1959, Glennan proposed a compromise to Quarles. Glennan's plan kept the contracts in the Air Force's name with NASA supplying the funds. The Air Force management team was to remain in the Air Force's pay but be physically located at NASA headquarters and report to NASA. Since the Vega and Centaur space vehicles both used an Atlas as the first stage, Glennan further proposed a coordinating team consisting of a NASA chairman and a representative from each of the following: ARPA, Air Research and Development Command, and the Jet Propulsion Laboratory, plus the Vega and Centaur project managers. NASA accepted responsibility for developing six Centaur upper stages and launching the Atlas-Centaur vehicles; payloads remained the responsibility of the mission agency.[28]

Glennan's plan required very close cooperation between NASA and the Air Force. What remained utterly inconceivable to some Air Force officers, however, was a military project essentially in the hands of civilians. They urged that control remain with ARPA and the Air Force. The stalemate remained until 10 June 1959 when Richard E. Horner, then NASA associate administrator, wrote to Herbert York, director of research and engineering, with a new plan to resolve the differences. Horner proposed that the Air Force establish the position of Centaur Project Director, filled by an Air Force officer, to be located at the Ballistic Missile Division of the Air Force at Los Angeles. The director would report to a Centaur program manager in NASA headquarters. The Ballistic Missile Division would provide only office space and administrative services. NASA would provide the Air Force project director with technical assistance and assign technical experts to him. Horner emphasized the need for a single line of authority from NASA headquarters to the project director. He also proposed a joint program management coordinating committee made up of a NASA member, an Air Force member, an ARPA member, and the project directors of Vega and Centaur, with Abe Hyatt of NASA as the chairman. This committee would periodically review the progress and resolve interface problems in addition to serving as a communication channel to the organizations involved. On 19 June, J. B. Macauley, York's deputy, responded to Horner and essentially agreed to his proposal. He assumed that the FY 1960 budget provided for six Atlas vehicles and recommended that the director of the military communications satellite program at the Ballistic Missile Division be an ex officio member of the coordinating committee. Horner quickly agreed and on 1 July 1959 Centaur was transferred from ARPA to NASA with scarcely a ripple. Lt. Col. John D. Seaberg remained the project director and Milton Rosen, the NASA program manager.[29] About the same time, Pratt & Whitney ran the RL-10 engine using liquid hydrogen and oxygen for the first time.

Summary

During the 1950s, development of high-energy rockets centered around the choices of hydrazine or ammonia with fluorine, and liquid hydrogen with fluorine or oxygen. Pratt & Whitney, a latecomer to rocket engine development, began to study hydrogen-fueled rocket engines in early 1956—the same time that the company began development of a hydrogen-fueled jet engine in the Suntan project. Despite a growing

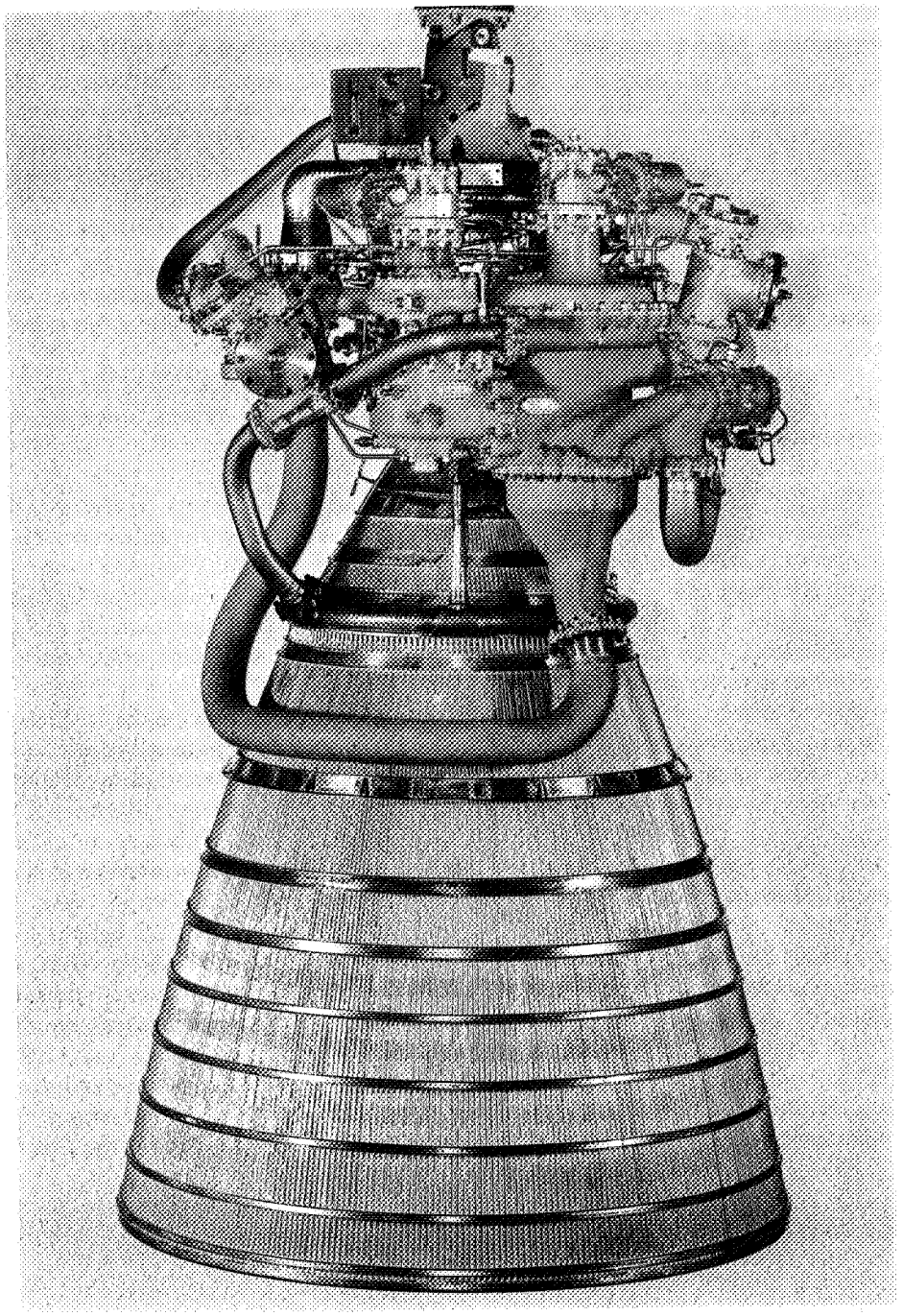

Fig. 52. Pratt & Whitney's RL-10 rocket engine, the first to use liquid hydrogen. Thrust, 67 kN at altitude; exhaust velocity, 4245 m/s; exit diameter, about 1 m. First engine run, July 1959; two of these engines powered the Centaur stage.

interest in high-energy rockets and a specific recommendation in late 1956 by the Air Force's Scientific Advisory Board to develop high-energy rocket engines, little was done until a series of stimuli about a year later: the faltering of the Suntan project, Russian satellite accomplishments, growing awareness of the military advantages of satellites, and the emerging role of the civilian space agency.

The first high-energy stage resulted from the efforts of Krafft Ehricke of General Dynamics–Astronautics. In December 1957, he proposed that the Air Force develop a hydrogen-oxygen upper stage for the Atlas using an engine designed by the Rocketdyne Division of North American Aviation. In the spring of 1958, the Air Force Suntan team proposed a hydrogen-fueled rocket engine using the Suntan experience of Pratt & Whitney and available facilities. Meanwhile, Abe Silverstein, a proponent for using liquid hydrogen in aircraft and rockets who was directly involved in such research since the early 1950s, was brought to Washington to head civilian space planning and projects. In the summer of 1958, spurred by the Air Force hydrogen engine proposal, military space needs, and Silverstein's planning activities, the Advanced Research and Projects Agency ordered Pratt & Whitney to develop a hydrogen-oxygen engine and General Dynamics–Astronautics to develop an upper stage for Atlas using the engine. This was to become the Centaur stage, intended to serve both military and civilian space needs. Despite some military objections, management control of Centaur was transferred to NASA in mid-1959. Silverstein's interest in hydrogen, aided by continued experiments at NASA Lewis laboratory, was a key factor in later decisions involving upper stages for the Saturn launch vehicle.